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THE GEOMETRY OF SATELLITE CLUSTERS.(U)
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THE GEOMETRY OF SATELLITE CLUSTERS

by

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SUMMARY

A preliminary examination has been made of some practical considerations affecting the choice of geometry for geosynchronous satellite clusters, including the constraints imposed by orbit dynamics, the effects of orbital perturbations and a possible need for spatial discrimination to allow re-use of inter-satellite link frequencies. Three cluster configurations which appear to deserve consideration involve satellites following, relative to the cluster centre,

(i) a common elliptical path in the equatorial plane,

(ii) a common circular path tilted at 30° to the horizontal, and

(iii) separate elliptical paths in parallel vertical planes inclined to the equatorial plane.

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LIST OF CONTENTS

1 INTRODUCTION

In response to the rapidly increasing demands for communications capabilities, successive generations of geostationary communications satellites have provided a progressive increase in individual capacity, and thus in the volume of interconnected communications capacity concentrated at individual locations on the geostationary orbit. Satellites now under development will each use a large part of the launching capability of the Space Shuttle, and it may well be that the requirements for the following generation will exceed the payload which could be carried in a single satellite during a single launch. One possibility foreseen to meet such an eventuality is the use of a large geostationary space platform, assembled in low earth orbit from elements carried there by several launching vehicles before being boosted to its assigned location in geostationary orbit; the single platform would allow economies through the use of common housekeeping systems, particularly for attitude and orbit control, but would imply a need for an in-orbit servicing capability, for repairs to the redundant systems and for addition of new payload elements. However, there is increasing interest in another possibility, the use of a closely-spaced cluster of individual near-geostationary satellites, which to a ground antenna would appear indistinguishable from a single satellite but in practice would be unconnected except by inter-satellite radio links. The cluster concept requires each satellite to carry its own housekeeping systems, but may simplify payloads by allowing each satellite to operate in a single frequency range only (apart from the inter-satellite links); this would make it relatively simple to replace failed or outdated satellites by others, whether of similar or different type.

The cluster concept has been advocated by Visher[1] and Wadsworth[2], while Staelin and Harvey[3] concluded that it has some significant advantages over large platforms. In a NASA/Convair/COMSAT presentation[4] to INTELSAT on geostationary platform concepts involving docked modules, the cluster concept was mentioned as an alternative approach; and INTELSAT's own programme[5] of Exploratory Research and Studies for 1981 includes a study of multiple satellite system architecture, involving "co-located satellites in revolving constellations (necklaces, figure-of-eights, stars) or fixed constellations (strings)". The most detailed studies, by Welti *et al*[6] for INTELSAT and by Wadsworth[2], assume the use of nominally geostationary satellites at longitudes spaced a short distance apart along the geostationary orbit. Other references[1,4,5] clearly envisage various types of rotating cluster, but are not specific as to the forms these might take; indeed, one reference[4] appears to illustrate a horizontal circle of five or six satellites, a configuration which is not compatible with the constraints of orbit dynamics (since, as will be shown, a ring-type configuration must involve a vertical component of motion).

The 1979 World Administrative Radio Conference allocated[7] two new frequency bands (22.55 to 23.55 GHz and 32 to 33 GHz) to the inter-satellite service, and these would presumably be used for opposite directions of transmission of the inter-satellite links connecting the satellites forming a cluster. (Other, higher frequency, bands may be usable in the more distant future.) Welti *et al*[6] considered channelisations and interconnection requirements suitable for the INTELSAT system, and their scheme would use virtually the whole of the allocated inter-satellite link (ISL) bandwidth at 23 and 32 GHz for connections between

just two co-located satellites. Wadsworth[2] assumed a larger number of nominally co-located satellites, but that each ISL would use not more than 10% of the allocated bandwidth. If we accept the possibility that one pair of ISLs may need to use virtually the whole of the available bandwidth, so that frequency discrimination may not be available as a means of increasing beyond two the number of satellites (and hence ISLs) in a cluster, then it may be necessary to consider using arrangements permitting frequency re-use, such as polarisation discrimination (using opposite senses of polarisation) and spatial discrimination (using well-separated antenna beams). Polarisation discrimination would allow doubling the number of links, with some technical difficulties, but for larger numbers of satellites it would appear necessary to consider spatial discrimination, which is clearly not available if the satellites are placed in line along the geostationary orbit so that there is no difference in bearing between the various ISL beams.

From these considerations, it appeared that there was a need for a preliminary assessment of feasible cluster geometries, compatible with the constraints of orbit dynamics, and that it would also be of interest to establish which of these configurations would ensure separation of the sight-lines of the ISL beams in order to permit frequency re-use through spatial discrimination. The work described in this Report was intended to provide such an initial assessment, without attempting to consider all the possible implications.

2 BASIS FOR SELECTION OF ORBITAL ELEMENTS

We assume that satellites forming part of a cluster would be maintained within a few kilometres of one another and of a point which we shall call the cluster centre. We further assume that their orbital elements would be chosen such that, in the absence of orbital perturbations (in particular due to the gravitational effects of the non-spherical earth, the moon and the sun) the proximity of the satellites in the cluster would be maintained without any need for the propulsion systems on the satellites to provide continuous thrust. This implies that the satellites in the cluster (and the cluster centre itself) share a common value of the orbital element a (semi-major axis), and that other orbital elements of the individual satellites have small differences from the orbital elements of the cluster centre (it being these differences that define the geometry of the cluster). In practice the satellite propulsion systems would be required to correct the orbital perturbation effects, and in doing so to maintain the relative positions of the satellites to a high degree of accuracy; an appropriate objective might be to ensure that any errors occurring in the desired differences between the orbital elements of a satellite and those of the cluster centre would be at least an order of magnitude less than the chosen differences themselves.

For the purposes of this preliminary examination, we further assume that the cluster centre is located at a geographically fixed point on the geostationary orbit. Using suffix 0 to denote the cluster centre and suffices A, B, C etc for the individual satellites in the cluster, we follow the notation and numerical values used by Merson[8] and assume that inclination i_0 and eccentricity e_0 are both zero and that $a_0 = 42165.8$ km. In these circumstances the other elements of the cluster centre – Ω_0 (right ascension of the ascending node), ω_0 (argument of perigee) and M_0 (mean anomaly,

equal to $2\pi(t - \tau_0)/P$, where P denotes period and τ time of perigee passage) - are not individually definable; its right ascension (*ie* its equatorial longitude relative to the first point of Aries) is equal to the sum $\Omega_0 + \omega_0 + M_0$, while the variation of M_0 with time is such as to result in a geographically fixed longitudinal position λ_0 . The mean longitude of an individual satellite, *eg* λ_A , may be chosen equal to or slightly different from λ_0 , so that its mean distance $(L_A - L_0)$ from the cluster centre is equal to 42165.8 $(\lambda_A - \lambda_0)$ km, and if the satellites have small values of e and i their instantaneous distances from the cluster centre, relative to earth axes*, are given by:

radial position (positive upward) $\Delta r_A = - a_A e_A \cos M_A$;

latitudinal position (positive northward) $\Delta K_A = a_A i_A \sin(M_A + \omega_A)$;

longitudinal position (positive eastward) $\Delta L_A = a_A[\lambda_A - \lambda_0 + 2e_A \sin M_A - \frac{1}{4} i_A^2 \sin 2(M_A + \omega_A)]$.

It is the term in i^2 in the longitudinal position which produces the figure-8 effect in the ground track of a geosynchronous satellite which is significant for larger values of i . However, here we are considering only very small values of i , so that the term in i^2 may be ignored. With this deletion, substituting for a_A , and assuming that i will be measured in degrees rather than radians, these equations become:

$$\Delta r_A = - 42165.8\, e_A \cos M_A \text{ km;}$$

$$\Delta K_A = 735.932\, i_A \sin(M_A + \omega_A) \text{ km;}$$

$$\Delta L_A = (L_A - L_0) + 84331.6\, e_A \sin M_A \text{ km.}$$

Thus to control the geometry of the satellite cluster the elements at our disposal, for each satellite in the cluster, are λ, e and M (or τ), and i and ω . Varying the value of λ varies the mean longitude of the satellite to east or west. Introducing a small value of e (with $i = 0^\circ$) changes the satellite path (as seen in earth axes relative to the cluster centre) from a fixed point on the geostationary orbit to a small ellipse in the equatorial plane with the fixed point at its centre, the major axis of the ellipse (lying horizontally, east and west) being double the minor (vertical) axis; varying the time of perigee passage τ for different satellites results in differing values of M . Introducing a small value of i (with $e = 0$) causes the satellite to perform a simple harmonic motion along a virtually straight horizontal line lying north and south, its phasing depending on the value of ω . Introducing small values of both e and i twists the elliptical path associated with e out of the equatorial plane, the direction of twist depending on the value of ω : if $\omega = 0^\circ$ or 180° the minor axis remains vertical but a north-south component is added to the major axis, so that it runs

* Except where otherwise stated, we shall describe a cluster in terms of axes fixed relative to the earth and with origin at the cluster centre, describing the axis radial to the centre of the earth as vertical (up/down) and the other two orthogonal axes as horizontal (north/south and east/west).

from north-east to south-west if $\omega = 0^{\circ}$ or from north-west to south-east if $\omega = 180^{\circ}$; if $\omega = 90^{\circ}$ or 270° the major axis remains east-west but a north-south component is added to the minor axis, so that its upper end (at the apogee of the orbit) is tilted towards the south if $\omega = 90^{\circ}$ or towards the north if $\omega = 270^{\circ}$; while for intermediate values of ω, both axes are twisted out of the equatorial plane.

The orbital elements of the individual satellites in the cluster may be chosen to take advantage of these effects in various ways on the different satellites, so producing a variety of cluster geometries. However, it would appear that a small non-zero value of e is necessary in all cases where spatial diversity is required between the ISLs, this being the only method of ensuring vertical separation of their sight-lines; and it is also necessary for any rotating configuration.

When the positions of individual satellites relative to the cluster centre have been determined, the geometrical relationships between any two satellites may be determined as follows:

horizontal distance to B from A $\quad d_{AB} = \sqrt{(\Delta K_B - \Delta K_A)^2 + (\Delta L_B - \Delta L_A)^2}$ km;

range to B from A $\quad P_{AB} = \sqrt{d_{AB}^2 + (\Delta r_B - \Delta r_A)^2}$ km;

azimuth of B from A $\quad A_{AB} = \arctan\left[(\Delta L_B - \Delta L_A)/(\Delta K_B - \Delta K_A)\right]$;

elevation of B from A $\quad E_{AB} = \arctan\left[(\Delta r_B - \Delta r_A)/d_{AB}\right]$.

Apart from ensuring an adequate separation of the ISL sight-lines, for which the specific requirement would depend on the ISL antenna diameter, the cluster geometry is likely to have to be chosen with two other requirements in mind:

(a) in order to ensure that the cluster appears, to a ground antenna, indistinguishable from a single satellite, the positions of the individual satellites, projected radially onto a horizontal plate through the cluster centre, should always be enclosable within a circle of specified radius, which would be a function of ground antenna diameter and operating frequency; and

(b) the pointing angle requirements of individual ISL antennas mounted on the satellites should be limited to a cone of specified semi-angle.

Moreover, it would probably be necessary for each satellite to carry sufficient ISL antennas to enable it to operate in any position in the cluster.

In the following section, numerical examples are examined for three specific types of cluster geometry which appear to be potential candidates for meeting a requirement for spatial diversity between ISLs. For this purpose, arbitrary numerical values have been assumed for the requirements (a) and (b) above. For (a) it is assumed that, without any allowance for station-keeping errors, the nominal satellite positions should be enclosable within a horizontal circle of 10 km radius; this might correspond to about 11 km radius with station-keeping errors. (Welti *et al*[6] adopted a more severe requirement, corresponding to 6.25 km radius.) For (b) it is assumed, following Welti *et al*[6], that ISL

tracking requirements should be limited to a cone of 45° semi-angle; again assuming station-keeping errors of about 10%, this is reduced to 40° semi-angle in terms of the nominal satellite positions. In each case the examples have been calculated for a cluster of four satellites, using spatial diversity only.

It should be noted that the assumption that the cluster centre is located at a geographically fixed point on the geostationary orbit, introduced to simplify the initial analysis, cannot be expected to hold strictly true in practice; orbital perturbations will rapidly modify the elements of all the satellites, and hence of the cluster centre, as discussed further in section 4. However, their effect will be primarily on the motion of the cluster as a whole, rather than on the relative motion of the satellites within the cluster; indeed, whatever the values of the elements of the cluster centre, suitable small differences in the elements of the individual satellites will reproduce a particular internal cluster geometry, such as could be achieved if the cluster centre were indeed geostationary, so that this simplifying assumption provides a legitimate starting-point for the examination of cluster geometry.

3 NUMERICAL EXAMPLES

3.1 Common elliptical path in the equatorial plane

Perhaps the simplest approach to providing sight-line separation is to make use of a small non-zero value of e, common to all satellites, with values of M for the four satellites separated by 90° intervals, and with $i = 0^{\circ}$ and $\lambda = \lambda_0$ for all satellites. The principle of such a cluster is illustrated in Fig 1 (using for clarity the unrealistically large value of $e = 0.2$), which shows the earth and the cluster as they would appear from a point on the earth's axis far beyond the south pole. Taking 00.00 as the time at which satellite A passes through perigee, this shows the change in appearance of the cluster after two successive intervals of 3 hours (*ie* of one-eighth of the period, which we shall refer to as being 24 hours, though it is strictly slightly less); as seen in space axes the cluster does not rotate, though its shape undergoes some distortion. However, if viewed relative to the rotating earth, and hence relative to the attitude of an earth-pointing geostationary satellite, the cluster would itself appear to be rotating once in 24 hours; using a suitably small value of e, the satellites would appear to follow, at equal intervals, a common elliptical path in the equatorial plane around the cluster centre. For this apparent elliptical path to extend over ±10 km in longitude we require $e = 10/84331.6 = 0.0001186$; the path then has a vertical minor axis of 10 km and a horizontal major axis of 20 km. Fig 2 shows the appearance of this cluster at 3 hour intervals, as seen (in earth axes) from a point to its south at the same altitude as the cluster.

As seen from one satellite (say A), two of the other satellites (B and D, with differences of $\pm 90^{\circ}$ in M) will appear to revolve around it in a common elliptical path in the equatorial plane, having a vertical minor axis of 14.14 km and a horizontal major axis of 28.28 km, *ie* with range varying between 7.07 km and 14.14 km. The other satellite (C, with a difference in M of 180°) will appear to follow a larger elliptical path around it, having a vertical minor axis of 20 km and a horizontal major axis of

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40 km, *ie* with range varying between 10 km and 20 km. As seen from A, C will always appear at any given elevation angle 3 hours after D, and B 3 hours after C; however, the separation of the sight-lines from one satellite to two other adjacent satellites, *eg* from A to B and C, will vary from a maximum of 79.3° to a minimum of 23.4°.

The variation in sight-line directions from A to B, C and D during 14 of the 24 hours is plotted in Fig 3. Superimposed on this plot are three parallel straight lines; these represent three sight-line directions with a constant separation of 45°, rotating (relative to the earth-stabilised satellite platform) at a constant rate of one revolution per day, and the actual directions show individual variations of about $\pm 20^{\circ}$ relative to these. Thus the ISL antenna pointing requirements could be met by three ISL antennas mounted on a platform making one revolution per day about an axis parallel to the earth's axis, with their mean pointing directions separated by 45°, but each having a range of movement for tracking purposes of $\pm 20^{\circ}$ (plus an allowance of perhaps 5° for orbital errors) relative to those mean directions. A triple-spin satellite, basically spin-stabilised but carrying such a rotating platform in addition to an earth-stabilised platform, is a conceivable design solution, but there appear better prospects for an alternative approach which is illustrated in Fig 4.

If eight ISL antennas were installed in a ring on an earth-stabilised satellite platform with their sight-lines covering different sectors of the equatorial plane, each could in turn track one of the other satellites at a time for a 3-hour period, the link being switched from one antenna to the next at the conclusion of each period. Fig 4 shows this, with the movements of antenna 1 drawn in heavier lines.

In this illustrative example, antenna 1 has a range of movement of $\pm 38^{\circ}$ (just less than the limit of $\pm 40^{\circ}$ which we assumed in section 2) about a mean elevation of 61°(W), *ie* a range from 81°(E) to 23°(W). At 20.00 it is pointing at 81°(E) elevation, waiting for satellite D to come within its field of view, which it does at about 20.42. For the next 12 minutes antenna 8 and antenna 1 both track satellite D, until by 20.54 the hand-over from antenna 8 to antenna 1 has been effected and antenna 1 alone continues to track satellite D. At 23.42 antenna 2 begins tracking satellite D; by 23.54 antenna 1 has completed the hand-over to it and swings back to 87°(E) elevation to begin tracking satellite C in preparation for taking over from antenna 8 by 00.06. By 03.06 it has handed over to antenna 2 and swings back to 86°(W) elevation in preparation for taking over the link to satellite B from antenna 8 by 03.18. Finally, by 06.18 it has handed over to antenna 2 at 23°(W) elevation and swings back to 81°(E) elevation, where it remains out of use until 20.42.

While antennas 1, 4, 5 and 8 require a range of movement of $\pm 38^{\circ}$, antennas 2, 3, 6 and 7 only require a range of movement of $\pm 16.5^{\circ}$. The latter range cannot usefully be increased, since the 3-hour interval between hand-overs is dictated by the need to coordinate with the other antennas needing the larger range.

3.2 Common circular path tilted at 30° to the horizontal

If a small non-zero value of i is introduced into the orbit of each satellite in the cluster discussed in section 3.1, while retaining the same value of e, the north-

south component thus introduced twists the elliptical path out of the equatorial plane. As previously noted, if $\omega = 90^{\circ}$ or 270° the effect is to leave the path's major axis unchanged, lying horizontally in the equatorial plane, and to add a north-south component to the minor axis only. If $\omega = 90^{\circ}$ the apogee is in the southern hemisphere and the perigee in the northern, while if $\omega = 270^{\circ}$ the perigee is in the southern hemisphere and the apogee in the northern. For this example we have arbitrarily chosen to use the value $\omega = 270^{\circ}$ for the four satellites in the cluster.

To produce a north-south component of ±10 km would require that $i = 10/735.932 = 0.01359^{\circ}$. The projection of the path onto a horizontal plane would then be a circle of 10 km radius, giving the largest separation between satellites permitted by our assumed requirement (a), with the path itself tilted at arc tan 0.5, *ie* 26.6°, to the horizontal. However, it appears preferable to use a slightly smaller value, $i = 0.01177^{\circ}$, at which the path itself is a circle of 10 km radius tilted at arc sin 0.5, *ie* 30.0°, to the horizontal, and its projection on the horizontal plane is an ellipse with semi-minor axis of 8.66 km in the north-south direction. If the four satellites have values of M separated by 90°, so that they are equally spaced around this circular path, each will see the others as apparently moving in circular paths around it; A will see B and D at a constant range of 14.14 km and C at a constant range of 20 km. The sight-lines from A to B and C will have a constant separation of 45°, as will those from A to C and D, and all three sight-lines will rotate at a constant rate of one revolution per day.

A rotating ISL antenna platform with its axis at 60° to the horizontal appears unlikely to be practicable. The alternative solution of a ring of individually tracking antennas also appears impracticable on a spin-stabilised satellite, but is probably feasible on a three-axis-stabilised satellite; the 30° tilt of the ring plane would help to keep the sight-lines of north-facing and south-facing antennas clear of the rotating solar arrays likely to be protruding from the northern and southern ends of such a satellite. It would be possible to reduce the number of ISL antennas to seven, but in order to maintain symmetry it seems more likely that eight would be used, and such an example is illustrated in Fig 5 in similar manner to Fig 4. The north-facing antenna 1 needs a tracking range of $\pm 27^{\circ}$, centred on 0° azimuth, instead of our assumed maximum of $\pm 40^{\circ}$; each of the other antennas needs a similar range, with their mean pointing directions separated by 45°. Antennas 2, 3 and 4 could be mounted on the east face of the satellite body, and antennas 6, 7 and 8 on the west face.

3.3 Separate elliptical paths in parallel vertical planes inclined to the equatorial plane

The cluster geometries considered in sections 3.1 and 3.2 each require either a rotating ISL antenna platform or a complete ring of individually tracking antennas between which the ISL signals are switched at approximately 3-hour intervals. In contrast the geometries assumed by Welti *et al*[6] and by Wadsworth[2], using nominally geostationary satellites (with e and i both zero) separated in longitude, allow any one ISL antenna on each satellite to track continuously one of the other satellites in the cluster, though they do not provide the sight-line separation which we are assuming

might be required under some circumstances. Clearly the use of satellites separated in longitude deserves consideration even when e and i are not zero; and, as noted in section 2, a small non-zero value of e appears essential if sight-line separation is to be provided.

However, a satisfactory configuration cannot be produced simply by taking the satellite orbits used in the clusters described in sections 3.1 and 3.2 and separating the mean longitudes of the satellites. In those clusters the satellite paths all lie in a single plane (vertical in section 3.1, tilted at 30° to the horizontal in section 3.2). This remains true if the satellite paths are separated in longitude; one satellite will then see the paths of two others, both either to east or to west of it, as superimposed straight lines (whether vertical or tilted) on which the satellites themselves will sometimes appear as superimposed, *ie* with no separation of the sight-lines to them.

This applies to the particular values of ω (90° or 270°) which were chosen, with a non-zero value of i, for section 3.2. However, as ω is varied from 90° or 270° the changing angle of twist of the elliptical path (as described in section 2) increases the apparent separation, as seen from east or west, of the north-going and south-going portions of the path; this effect is at a maximum when $\omega = 0^{\circ}$ or 180°, when the minor axis of the elliptical path is vertical and the (horizontal) major axis lies in a generally north-easterly to south-westerly direction (with $\omega = 0^{\circ}$) or north-westerly to south-easterly (if $\omega = 180^{\circ}$). This would appear to be the preferred approach for satellites separated in longitude.

If a cluster is formed from satellites in such orbits, with $\omega = 0^{\circ}$ or 180°, one satellite will be seen from another, sufficiently different in mean longitude that it lies always either to east or to west of the first, as following an apparently elliptical path, the apparent size of the ellipse and its mean azimuth and elevation depending both on the longitudinal separation and on the difference in M for the two satellites, as well as on the actual amplitude of the motion of the satellites relative to the earth as determined by the values of e and i. If two of the satellites in the cluster were following similar paths, in parallel planes, with their values of M always equal, each would see the other as always due east or west, apparently at a fixed point.

In an initial examination of configurations of this type, each containing four satellites with their nodes separated by several kilometres in longitude and with ω equal to 0° or 180°, eight different configurations were examined; the values used for e and i were the same as those used in section 3.2 for the circular configuration, $e = 0.0001186$ and $i = 0.01177^{\circ}$, in order to minimise additional computation. The satellite with the most westerly node was identified as A in each case, with B, C and D having their nodes progressively further east, and 00.00 was again taken as the time at which A passed through perigee.

In three configurations (a, b and c) the four satellite paths were assumed to be parallel, with $\omega = 180^{\circ}$ in all cases; the values of M for adjacent satellites were separated by 90°, 120° and 180° for a, b and c respectively. In a further

three configurations (d, e and f) the paths were arranged in a 'W' pattern in plan view, with $\omega = 180^{\circ}$ for A and C but $\omega = 0^{\circ}$ for B and D in each case; the values of M were again separated by 90°, 120° and 180°, for d, e and f respectively. For the last two configurations (g and h) satellites A and D were made geostationary, with e and i both zero, while for the former configuration B and C followed parallel paths with their values of M separated by 180°, and for the latter configuration their paths formed a 'V' pattern, similar to half of the 'W', with $\omega = 180^{\circ}$ for B and $\omega = 0^{\circ}$ for C , and their values of M separated by 180°. The longitudinal separation of the satellite nodes was arbitrarily chosen in each case from within the range of values which appeared likely to be suitable. A ninth configuration was also examined, with $\omega = 235^{\circ}$ for all satellites and values of M separated by 180°; the results provided the expected confirmation that intermediate values of ω were less suitable than the values 0° and 180°, giving considerably smaller sight-line separations.

The initial results obtained for configurations a to h showed that the W patterns were inferior to the parallel-path patterns, giving much smaller values of minimum sight-line separation and larger variations in range. The four parallel-path patterns (a, b, c and g) were therefore carried forward to a second-stage examination; in this an estimate was made of the changes necessary to the parameters used in the initial calculations for each configuration just to meet the assumed requirements (a) and (b) of section 2, and hence of the effect these changes would have on the minimum separations achieved. This examination suggested that pattern b might provide a minimum separation of about 10°, with the other patterns giving values in the region of 7° to 8°. The particular advantage of pattern b is that the outer satellites of the cluster, A and D , are moving in phase with one another in similar parallel paths, and therefore see each other apparently at fixed points due east and west, while the ranges of B and C from A are such as to give fairly even separation of their apparent paths.

Pattern b was therefore selected for a full optimisation, the results of which are illustrated in Fig 6. The initial calculations had been based on the values $e = 0.0001186$, $i = 0.01177^{\circ}$ and 20 km spacing between the mean longitudes of adjacent satellites. As seen from satellite A, minimum angular separation occurred between satellite D (in its apparently fixed position due east) and satellite C when at an azimuth a little greater than 90°. In modifying these initial parameters, the procedure followed was:

(i) adjust the value of i to make the maximum southerly azimuth excursion of C as seen from A equal to its elevation when at 90° azimuth, with the aim of maximising the minimum separation;

(ii) retaining the resulting values of e and i , adjust the spacing of the satellite nodes to make the range of azimuth values of B as seen from A equal to 80°, in accordance with the assumed requirement (b) of section 2;

(iii) adjust the resulting values of e , i and the longitudinal spacing by a common factor (thus leaving angular relationships within the cluster unchanged) to make the positions of the four satellites at any one time, projected vertically

onto a horizontal plane through the cluster centre, always enclosable within a circle of 10 km radius.

This left final values of $e = 0.00003405$, $i = 0.00268^{\circ}$ and 6.67 km spacing between the mean longitudes of adjacent satellites, giving a minimum separation of 9.9° between the sight-lines from A to C and D. Fig 6a shows the sight-line directions from A to B, C and D at time 00.00, and the apparent paths they follow over 24 hours; figures outside the ellipses represent the time in hours, and those inside the ellipses the range in kilometres. These directions are representative of all those occurring between different satellites in the cluster, though for westward-looking links the mean azimuth direction is south of west instead of north of east. Fig 6b is a plan view of the cluster, showing the positions of the satellites at time 00.00 and the parallel inclined paths followed over 24 hours.

It should be noted that, while this configuration is instantaneously contained within a horizontal circle of 10 km radius, the centre of this circle moves through several kilometres during the course of a day. If it should be required to contain the configuration within a fixed 10 km circle it would be necessary to scale down the configuration further, reducing e, i and the longitudinal spacing accordingly.

The very small values of e and i found necessary for this configuration gave rise initially to some concern regarding susceptibility to the effects of orbital perturbations. For example, it is well known that the average rate of change of inclination due to lunisolar gravitational effects varies[8] between about 0.75 and 0.94 degrees per year, *ie* an overall average of about 0.0023 degrees per day, which is comparable to the actual value of i found appropriate for this configuration; also that the sign of the initial change in inclination depends on the value of Ω, which varies between the different satellites in the configuration because of their differing values of M with a common value of ω. The effects of orbital perturbations were therefore examined somewhat more closely, as described in section 4; but before this was done it was felt worthwhile to consider possible configurations having approximately the same value of Ω for all satellites in the cluster.

At first sight it appears that this is undesirable, bringing the sight-lines always close together, and for this reason no such pattern was included in the eight initially examined. However, if two different sizes of elliptical path were used, with A and D having smaller values of e and i than B and C, the sight-lines would then always be separated. In the extreme, e and i could be reduced to zero for A and D, resulting in a pattern similar to the pattern g previously considered, but with B and C having identical values of M instead of values separated by 180°. Such a pattern was therefore examined, using the same values of e, i and spacing of the mean longitudes as for pattern g, and was found to provide a minimum sight-line separation similar to that provided by pattern g.

It was further noted that, while in pattern g it is necessary to have identical spacings between the mean longitudes of each pair of adjacent satellites, this constraint does not apply to the revised pattern. Hence the dimensions of the pattern are not

uniquely determined by the need to meet the assumed requirements (a) and (b) of section 2, leading to a particular set of circumstances under which the sight-line separation is a minimum; instead, there is an additional degree of freedom permitting an optimisation procedure comparable to that used in a previous study[9] of satellite constellations, in which parameters are varied so as to improve the worst case conditions, while still meeting the necessary constraints, until another set of circumstances is found which would provide the worst case if the parameters were varied any further. In this instance it was found that optimum conditions occurred with the distance between the mean longitudes of B and C increased to 7.6 km, and the distance between the mean longitudes of the satellites forming the other adjacent pairs (A and B, C and D) correspondingly reduced to 6.2 km, while for B and C the value of e is 0.0000474 and of i is 0.00512°. Fig 7 shows, on the same basis as Fig 6, the antenna pointing directions for this configuration (representative of all those occurring within the cluster) and a plan view of the cluster. The minimum separation in this optimised configuration, occurring under two sets of conditions, is 8.2°.

The subsequent examination of perturbation effects, discussed in the following section, showed that restricting B and C to have approximately the same value of Ω (and hence of M) as A and D in the configuration of Fig 7 was not in fact necessary. It is also apparent that, in the configuration of Fig 6, the choice of 120° as the amount by which the values of M for B and C differ from the value for A and D is not necessarily optimum; it might be changed, and the longitudinal separation of the satellites and other elements re-optimised. Such changes might perhaps produce a configuration with a larger minimum separation than either of those described, but any improvement appears unlikely to be substantial, and the matter has not been pursued further at this stage.

4 EFFECT OF ORBITAL PERTURBATIONS

It might be expected that similar satellites, following similar orbits in close proximity, would experience very similar orbital perturbations. On the other hand it is well known, as noted in the previous section, that the sign of the initial change in inclination due to lunisolar gravitational effects depends on the value of the element Ω (the right ascension of the ascending node), and several of the cluster configurations under consideration use widely differing values of Ω for the different satellites. The resolution of this apparent conflict of expectations was not immediately apparent, so it was considered necessary to examine the effects of perturbations on orbits with very small values of e and i in somewhat greater depth.

To assist in this examination, R.H. Gooding made available a specially modified version of the computer program TCSKEF[10]. This analytical orbit generator includes the long-period, but not any short-period, perturbation effects; however, its use was appropriate to the main objective of distinguishing the effects in the short term of the long-period perturbations on the different satellites in a cluster.

084

The primary concern was to clarify the effect of the lunisolar gravitational perturbations on the inclination of satellites having small initial values of i and different values of Ω. Such effects are conveniently illustrated on a polar plot of i (radially) versus Ω (circumferentially). Allan and Cook[11] illustrated the long-term

development of the values of i and Ω for an initially geostationary orbit, not subject to any orbital adjustments, with starting dates corresponding to four different positions of the lunar orbit. The four curves are broadly similar; an average of them would approximate to a circular arc on the $i - \Omega$ diagram (as shown in Fig 8a), proceeding clockwise from the origin about a centre at $i = 7.5^{\circ}$, $\Omega = 0^{\circ}$, and taking about 26 years to reach $i = 15^{\circ}$ and about 53 years to complete the circle and return to the origin. The first year thus produces, on average, a change in i of about 0.9° in the direction corresponding to $\Omega = 90^{\circ}$E, though in practice the centre of curvature varies and the annual rate of change may be between 0.75° and 0.94°, as already noted.

One of the starting-points considered by Allan and Cook[11] was July 1978, which was a month during which the rate of change of inclination was at a maximum. It was therefore selected as the month for which the program TCSKEF was used to calculate the day-by-day change in i and Ω (among other elements) for an initially geostationary satellite, and the results obtained are plotted in Fig 8b. It is seen that the overall change in i for the month is about 0.08° in the direction corresponding to $\Omega = 100^{\circ}$E, but that the daily changes vary considerably in magnitude and direction at different times in the lunar period.

The largest daily changes in i during the month occurred on 18 and 19 July. TCSKEF was used to calculate the orbital changes on those days, at 6 hour intervals, for satellites all having initial values of i of 0.00268° but initial values of Ω of 30°, 150° and 270° respectively (thus producing a similar configuration to the cluster of section 3.3 and Fig 6, in which two of the four satellites have the same value of Ω); the results are plotted in Fig 8c. It is seen that, though the value of i for satellite C initially falls almost to zero before increasing again, while the values for satellites A and B are increasing throughout, the overall effect is a steady translation of the cluster as a whole across the diagram, with no significant effect on the relative positions of the satellites. Maintenance of the relative positions of the satellites on this diagram also indicates maintenance of the daily pattern of their relative positions in space, despite the increasing amplitude of movement of the cluster as a whole.

The short-period perturbations associated with the orbital motion of the satellite, which are not reproduced by TCSKEF, do not appear in Fig 8c. Examples of such perturbations were illustrated by Merson[8]. If included they would appear superimposed on the three parallel curves of Fig 8c as small oscillations of 12-hour period affecting all three satellites similarly.

While this discussion has concentrated on the lunisolar perturbations of inclination, broadly similar comments apply to other perturbations affecting other orbital elements of the satellites forming a cluster, in that their effect will be primarily on the cluster as a whole rather than on its internal configuration.

Though fears of substantial differential perturbations due to natural causes are thus alleviated, the overall effects of perturbations on the cluster as a whole will still need correction, and this can only be done by use of the propulsion systems on the individual satellites, introducing a risk of disturbing the cluster geometry in the

process. Since the average daily change in i, for example, is of a magnitude comparable to the dimensions of the cluster, it would probably be desirable to make any necessary corrections in the smallest possible increments compatible with maintaining propulsion system efficiency, and if possible to make them simultaneously on all satellites in the cluster. However, it only appears necessary to correct for an appropriate portion of the average long-term perturbation effects, not to attempt to correct for the varying daily effects, thus avoiding a significant addition to the total fuel requirement. It would require more detailed study to establish an optimum station-keeping strategy taking all these considerations into account.

5 DISCUSSION

It is beyond the scope of this paper to assess all the practical considerations affecting a choice between the three types of cluster geometry considered in section 3, should a geometry providing spatial discrimination be required. However, comparisons may be drawn between the three approaches in various respects, even if the relative weights which should be attached to these various comparisons are uncertain.

The appearance of the four principal configurations described in section 3 is compared in Fig 9, in which they are drawn to a common scale in isometric projection, showing satellite positions at time 00.00 relative to axes fixed in relation to the earth and with origin at the cluster centre.

The vertical ellipse of section 3.1 and Fig 9a appears best suited for use with spin-stabilised satellites, and the tilted circle of section 3.2 and Fig 9b with three-axis-stabilised satellites. The parallel-path configurations of section 3.3, two examples of which are shown in Fig 9c&d, are suitable for use with either type of satellite, and hence appear the most suitable choice if the cluster were to include a mixture of satellite types.

For a four-satellite cluster with the assumed dimensional limitations, the parallel-path configurations require a total of six ISL antennas mounted on each satellite if the satellite is to be capable of being used in any position in the cluster. Only three of the six antennas would normally be in use at any one position, so if one of the three antennas in use should suffer a failure of its tracking system then another antenna would be available to be brought into use immediately if the satellite were in one of the central positions B or C, or the satellite might be able to exchange positions with its neighbour, so that the failed antenna would no longer be needed, if it were initially in one of the outer positions A or D. The tilted circle and the equatorial vertical ellipse each involve (on the assumptions quoted) satellites carrying eight ISL antennas; with the circle, a small increase in the antenna tracking range would provide redundancy in the event of a tracking failure of one antenna, but this would not be the case with the ellipse.

The parallel-path configurations allow for continuous tracking without any switching between antennas; the tilted circle and the equatorial vertical ellipse each require ISL switching from one antenna to the next approximately every 3 hours.

The range between any particular pair of satellites is constant for the tilted circle, but varies by a factor of 2 for the equatorial vertical ellipse and by a larger factor for the parallel path configurations.

Orbital perturbations will have their main effect upon the cluster as a whole, rather than on the internal geometry of the cluster. Their correction must be planned so as to have minimum adverse effect on the internal geometry of the cluster without unduly increasing fuel consumption; this aspect requires further study. The parallel-path configurations are likely to require tighter station-keeping than the others, due to their smaller basic values of e and i and the smaller sight-line separations they provide.

In the numerical examples considered, with four satellites in the cluster, the minimum ISL sight-line separations provided are 45° with the tilted circle, 23.4° with the equatorial vertical ellipse, and 9.9° and 8.2° respectively for two parallel-path configurations. If the number of satellites in the cluster had been chosen as three, these figures would become 60° for the tilted circle, 32.2° for the equatorial vertical ellipse, and at least 16.4° (not optimised) for the parallel-path configurations. All these values are subject to reduction by the effects of orbital errors. No attempt has been made here to determine a minimum acceptable value for the sight-line separation, which will be dependent on the ISL design.

With either the tilted circle or the vertical ellipse, the satellite spacing may readily be adapted to accommodate a larger number of satellites in the cluster than four (all following the same path relative to the cluster centre) with only a moderate reduction in the minimum separation of the ISL sight-lines. The particular parallel-path configurations discussed in section 3.3 are not suitable for use with more than four satellites, since some sight-lines would coincide, and while other variants of these patterns would have positive sight-line separations, their minimum values would be small; hence this type of pattern appears unsuitable for use with more than four satellites in a cluster requiring spatial discrimination only, though use of polarisation discrimination as well would allow the number to be increased.

It should be noted that, in the case of the vertical ellipse, the sight-line of each ISL would cross the earth's surface once per day. While the risk of interference is probably very small, it would need examination[12].

In sections 3.1 and 3.2 it was assumed that all satellites in the cluster would follow a common elliptical or circular path around the cluster centre. While this will maximise the sight-line separations, it is not an essential requirement; paths of somewhat different sizes could be used, and indeed are likely to occur in practice as a result of orbital errors.

In section 2 it was suggested that orbital errors as between the satellites in a cluster would need to be kept an order of magnitude smaller than the small differences in orbital elements deliberately introduced. One example of experience in this respect was provided in October 1978, when INTELSAT was in process of transferring services from satellite INTELSAT IV F-1 to INTELSAT IV-A F-6, and adjusted their orbits to maintain the

satellites close together for this purpose. Their orbital elements as reported[13] at 31 October 1978 differed by $\Delta e = 0.0000076$, $\Delta i = 0.0049^{\circ}$ and $\Delta(\Omega + \omega + M) = 0.0048^{\circ}$, which would correspond to $\Delta L = 3.5$ km if e and i were both zero; such an error in e could probably be accepted for clustered satellites, but the differences in i and L, if regarded as errors, would need to be reduced by an order of magnitude. The writer is not aware whether these were typical station-keeping errors as between these two satellites, or how much effort was being made to reduce them; in any case, the tracking facilities available were limited[14] to range and angle data on one satellite and two-station angular data only on the other satellite, without benefit of the inter-satellite measuring facilities which would almost certainly be provided for clustered satellites. Station-keeping within a cluster appears likely to be a testing, but by no means an impossible, requirement; indeed, many examples of satellite rendezvous show what can be achieved with sufficient effort.

In his original article on satellite clusters, Visher[1] envisaged a single switching satellite at the centre of a cluster, having links to each of the satellites clustered around it, which would not apparently need to have links to one another. Our discussion has been based on the concept used by Wadsworth[2], and likely to be necessary to INTELSAT, in which each satellite has links to every other satellite in the cluster. With the latter concept, it would be a disadvantage to have a satellite at the centre of a cluster of satellites following an elliptical or circular path around it; with an odd number of satellites in the outer ring, the addition of the central satellite would halve the minimum ISL sight-line separation otherwise available, and with an even number of satellites it would reduce it to zero.

6 CONCLUSIONS

The individual satellites making up a small orbital cluster of nominally co-located satellites will, relative to the cluster centre, have small differences in some or all of their eccentricity, inclination and geographical nodal longitude, and may also differ in their mean anomaly and nodal right ascension; only configurations compatible with such differences in orbital elements are feasible in practice. This rules out, for example, any suggestions for constant-altitude rotating systems.

If communications satellites are to be orbited in small clusters, there may be a need for cluster configurations allowing spatial discrimination between inter-satellite links. Three configurations which provide spatial discrimination have been examined; these involve satellites following, relative to the cluster centre,

(i) a common elliptical path in the equatorial plane,

(ii) a common circular path tilted at 30° to the horizontal, and

(iii) separate elliptical paths in parallel vertical planes inclined to the equatorial plane.

084 The first two of these have the disadvantage of needing inter-satellite link antennas able to track other satellites in the cluster through a full 360° of relative motion, but have the advantages of giving greater angular separation between the

inter-satellite links than does the third configuration, and of requiring less tight station-keeping. However, each of them has a range of other advantages and disadvantages, and all appear to deserve fuller examination in the light of any particular requirements that may arise. The strategy for correcting the effects of orbital perturbations, in particular, requires further study, especially as it affects the fuel consumption for station-keeping.

If spatial discrimination between inter-satellite links is not required, a cluster composed of truly geostationary satellites having a small longitudinal separation may well be the most appropriate choice.

Acknowledgments

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I am indebted to Dr D.K. Sachdev, Manager of the Research and Development Department of INTELSAT, for drawing my attention to several of the referenced papers and providing me with copies of them.

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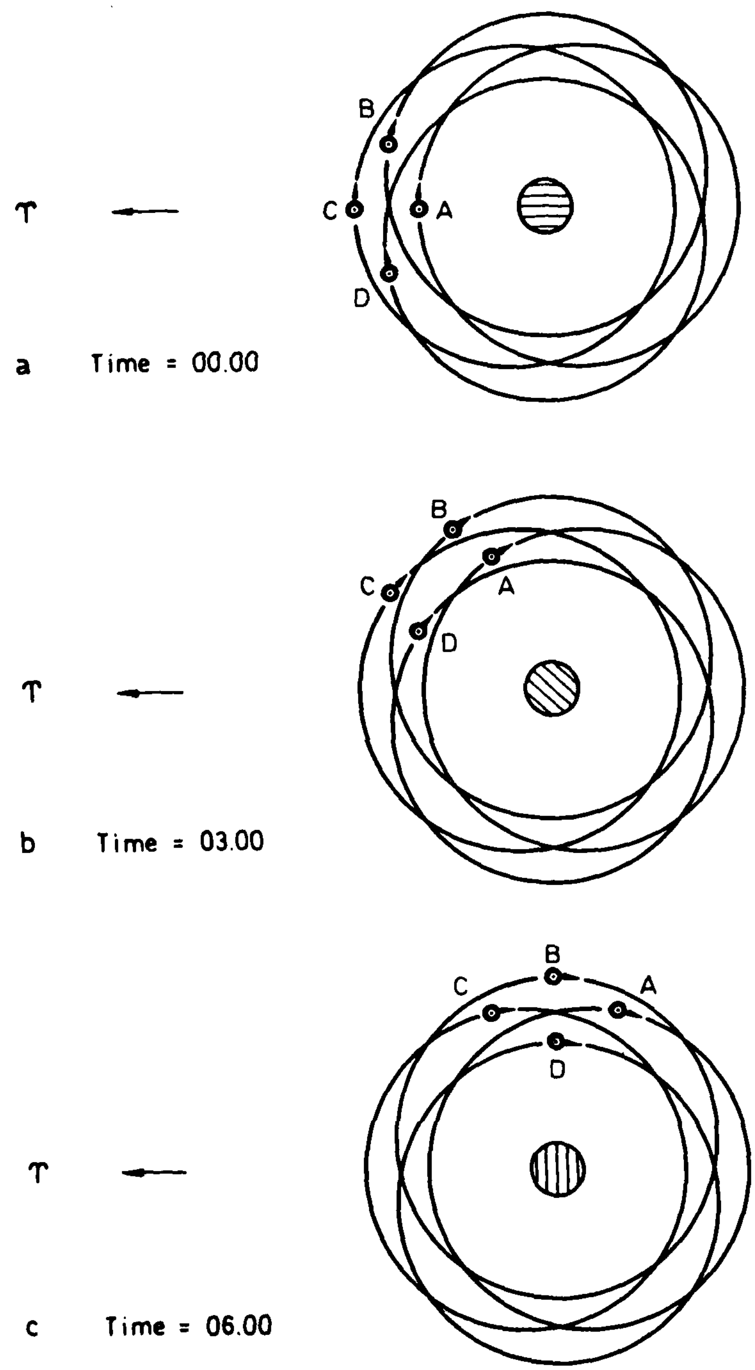

Fig 1a-c **Equatorial elliptical cluster (in space axes) as seen from the south**

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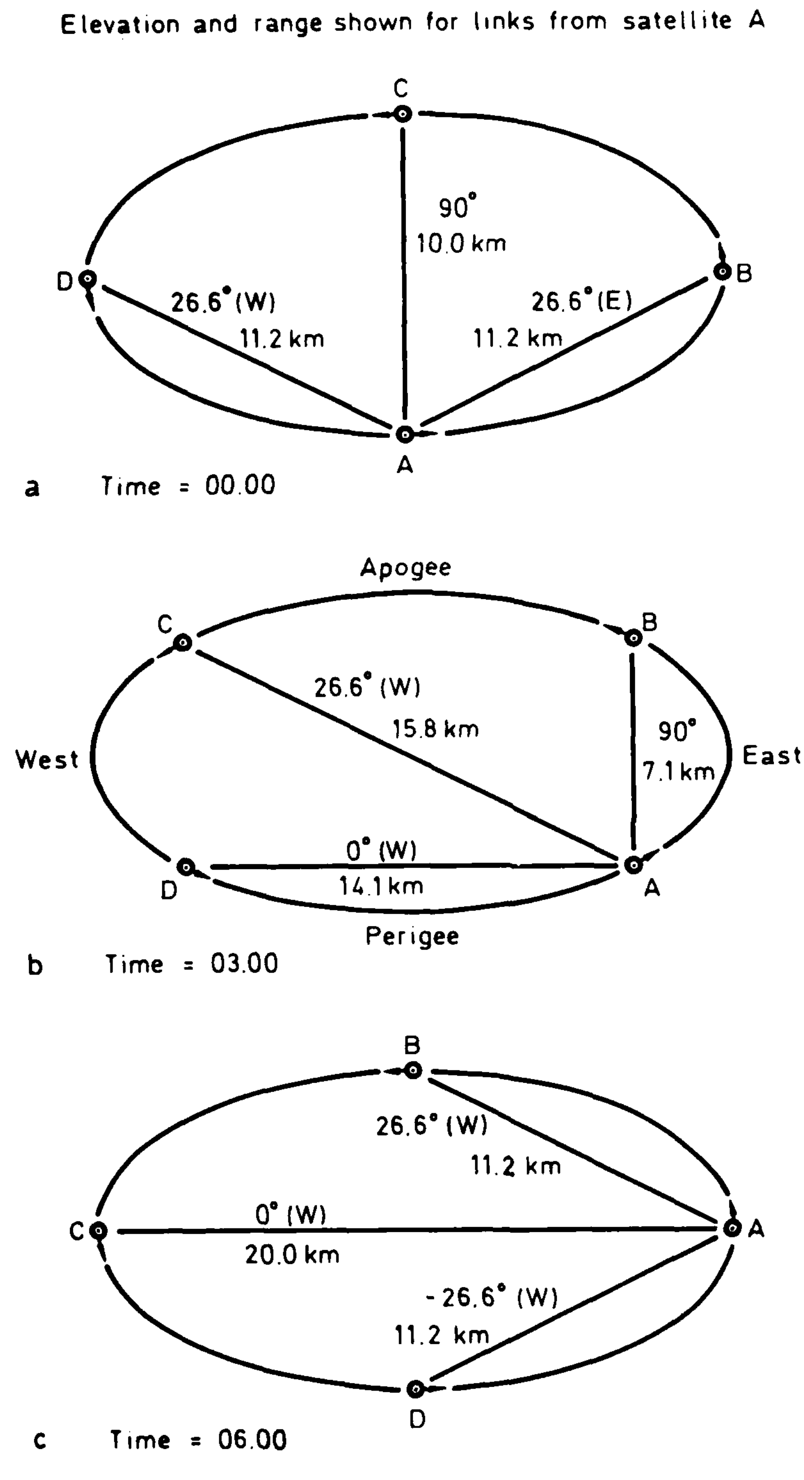

Fig 2a-c Equatorial elliptical cluster (in earth axes) as seen from the south

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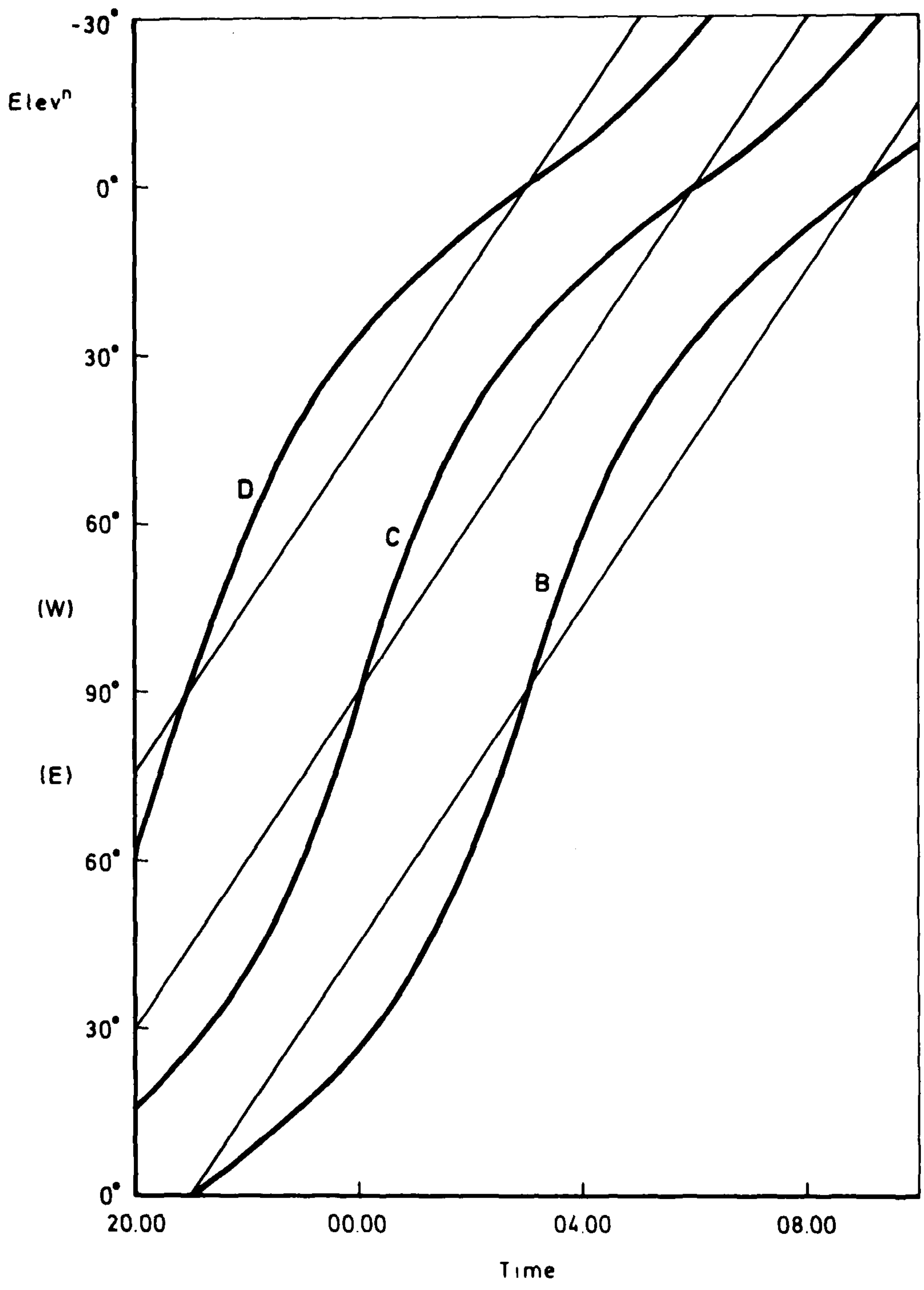

Fig 3 Equatorial elliptical cluster: ISL sight-line directions from satellite A

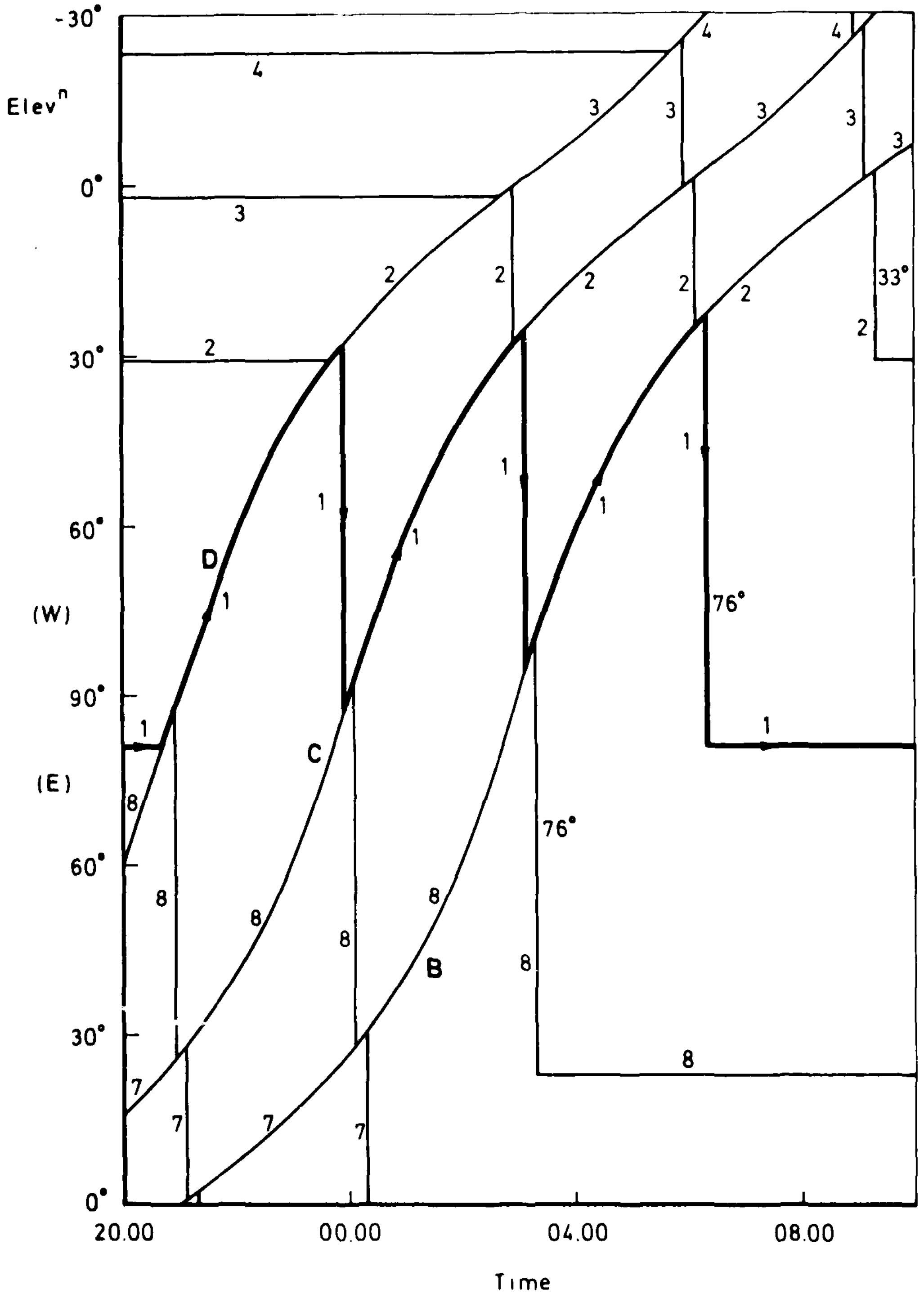

Fig 4 Equatorial elliptical cluster: ISL antenna pointing directions from satellite A

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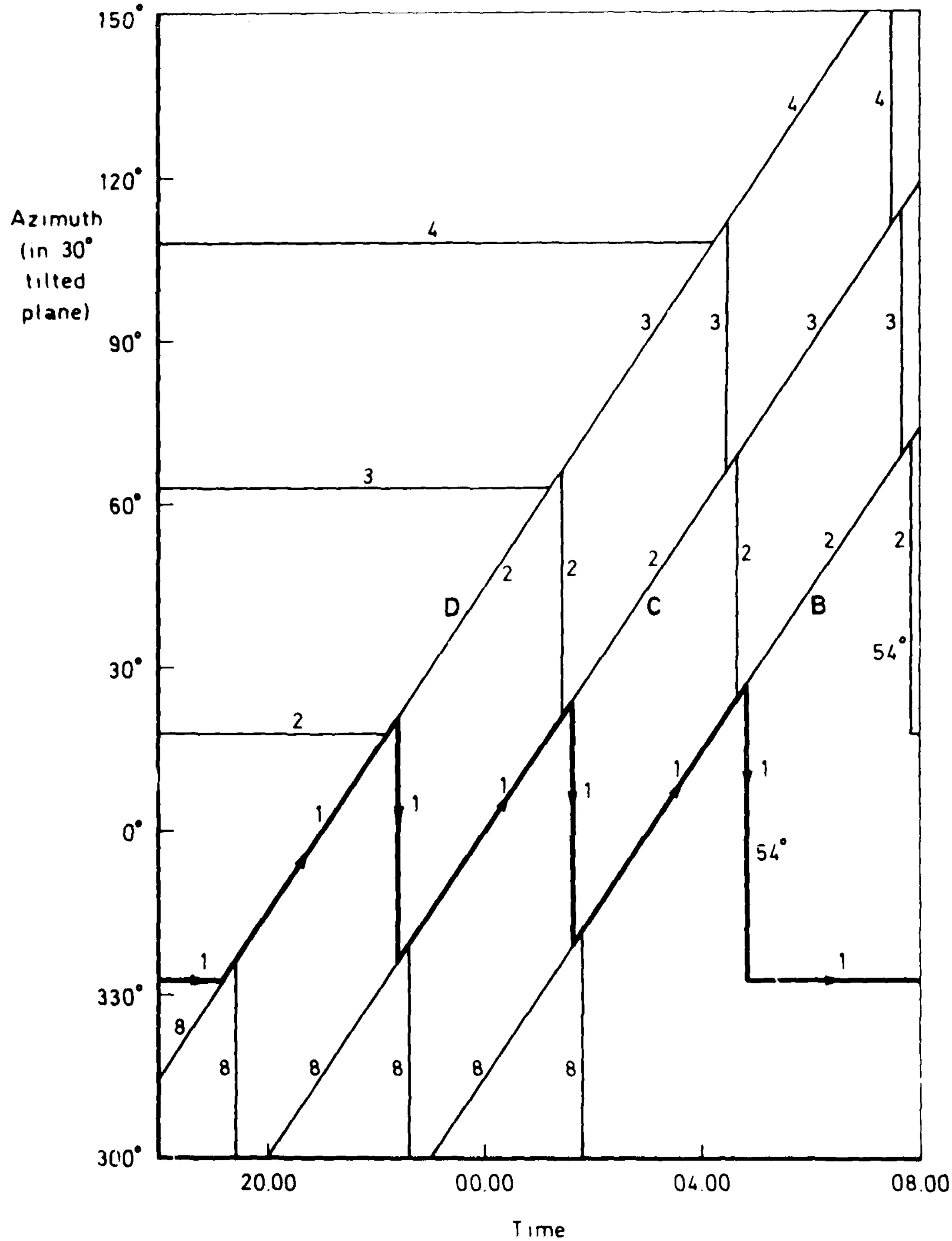

Fig 5 **Tilted circular cluster: ISL antenna pointing directions from satellite A**

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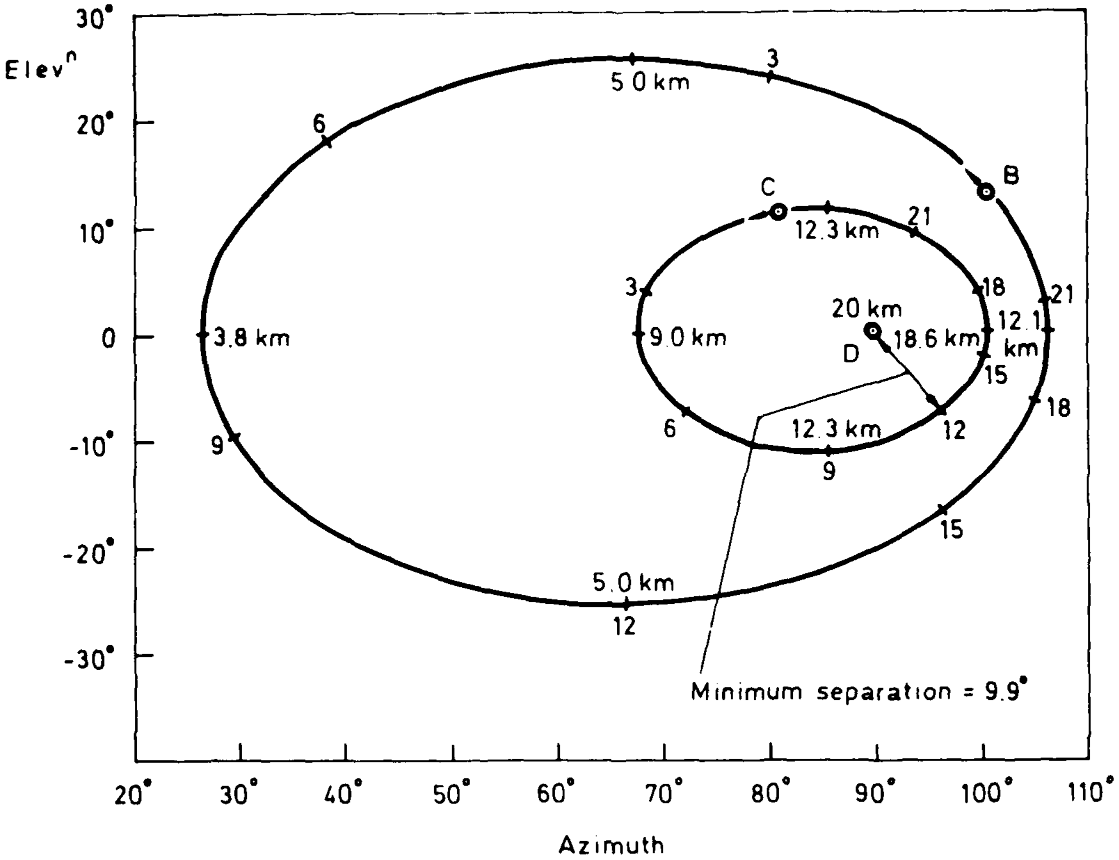
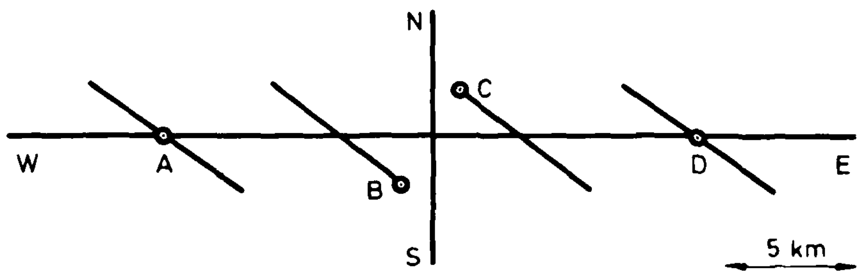
Range from A, and time (hours), are shown beside curves



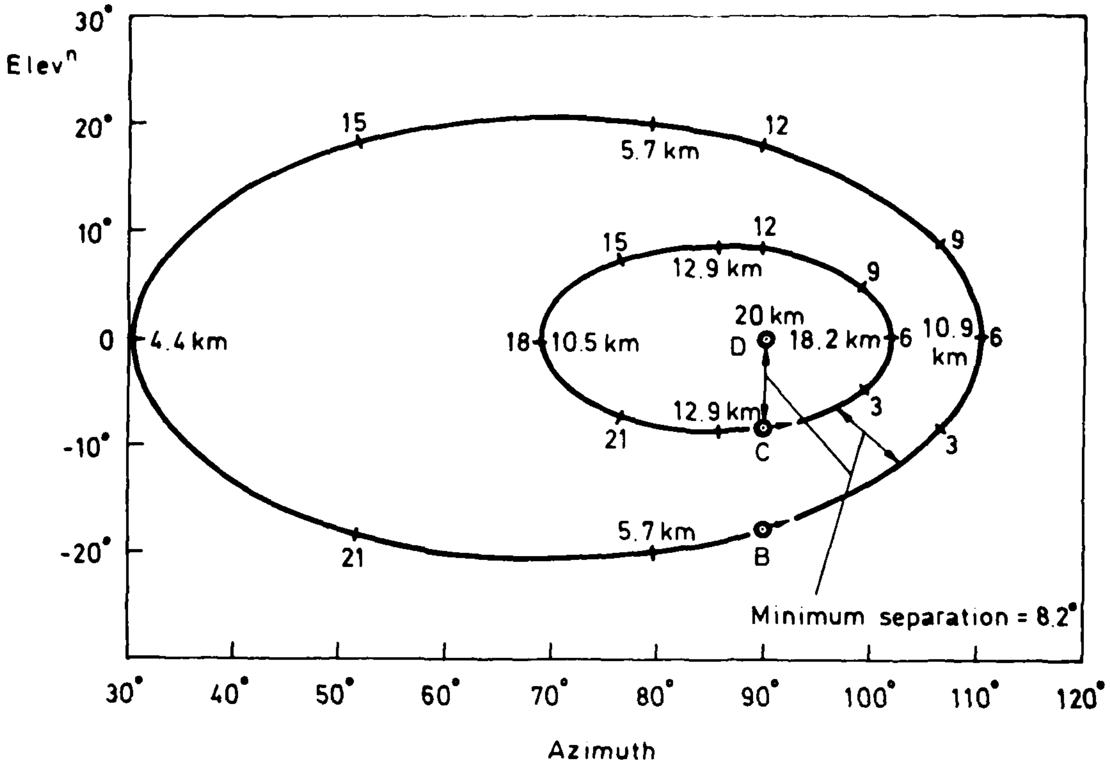
a ISL antenna pointing directions from satellite A



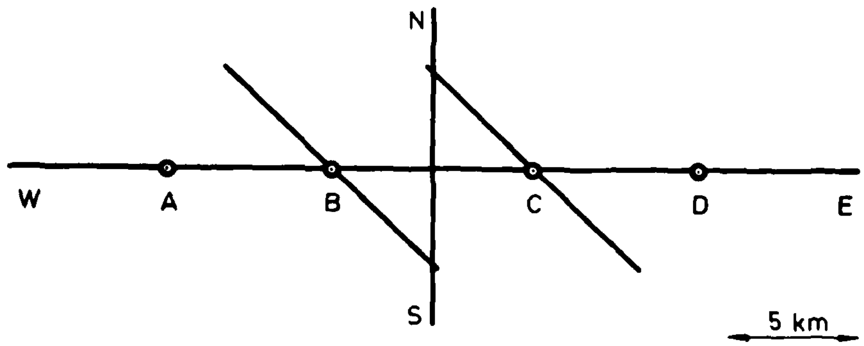
b Plan view of cluster

Fig 6a&b Four parallel inclined vertical ellipses

Range from A, and time (hours), are shown beside curves

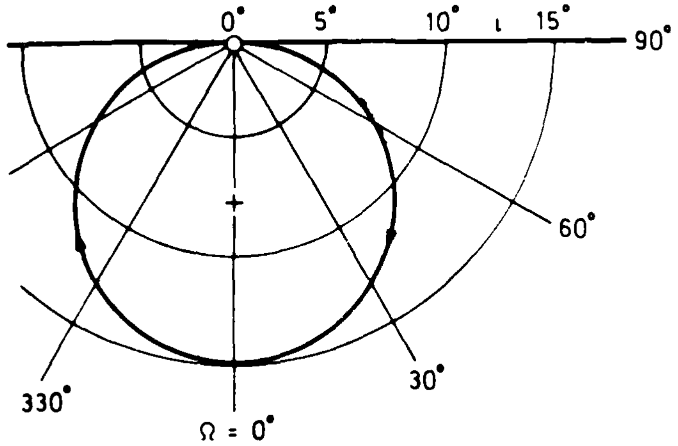


a ISL antenna pointing directions from satellite A

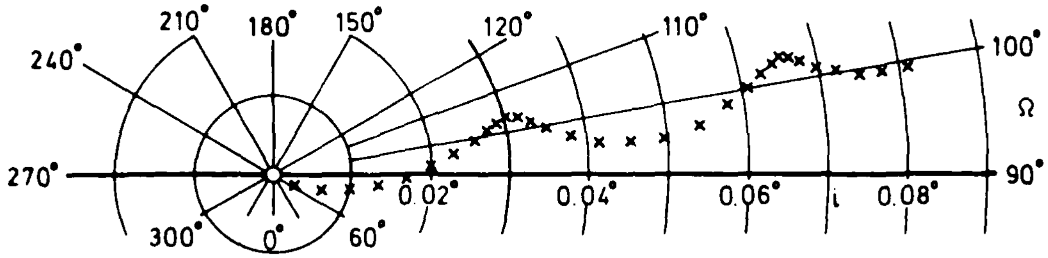


b Plan view of cluster

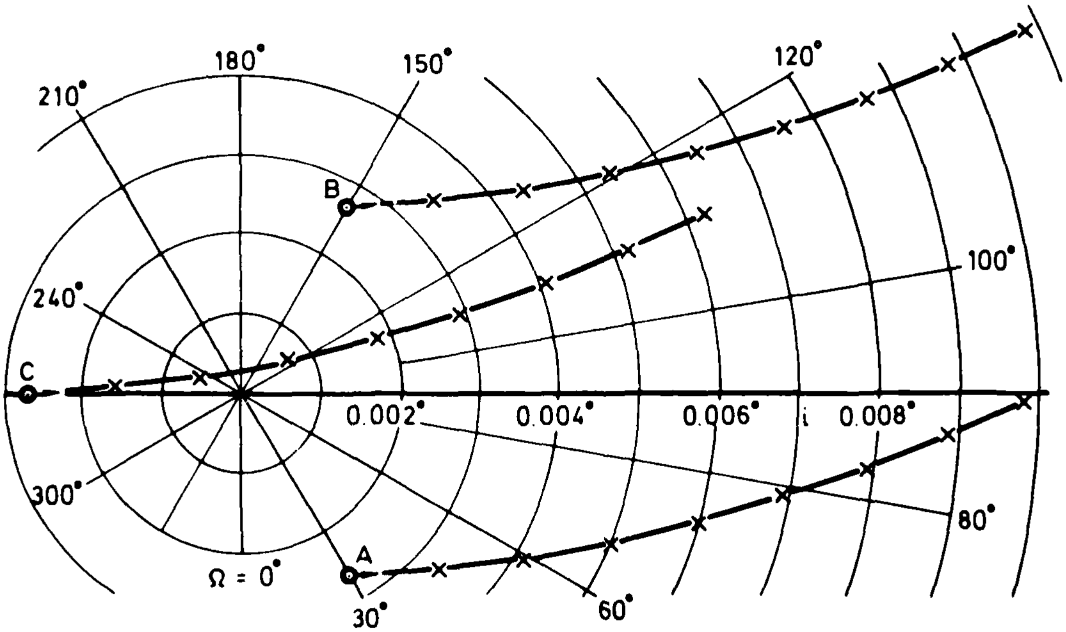
Fig 7a&b Two parallel inclined vertical ellipses and two geostationary satellites



a Averaged long - term perturbations



b Perturbations during month of July 1978



c Perturbations of cluster during two days (18 - 19 July 1978)

Fig 8a-c Perturbations of i and Ω

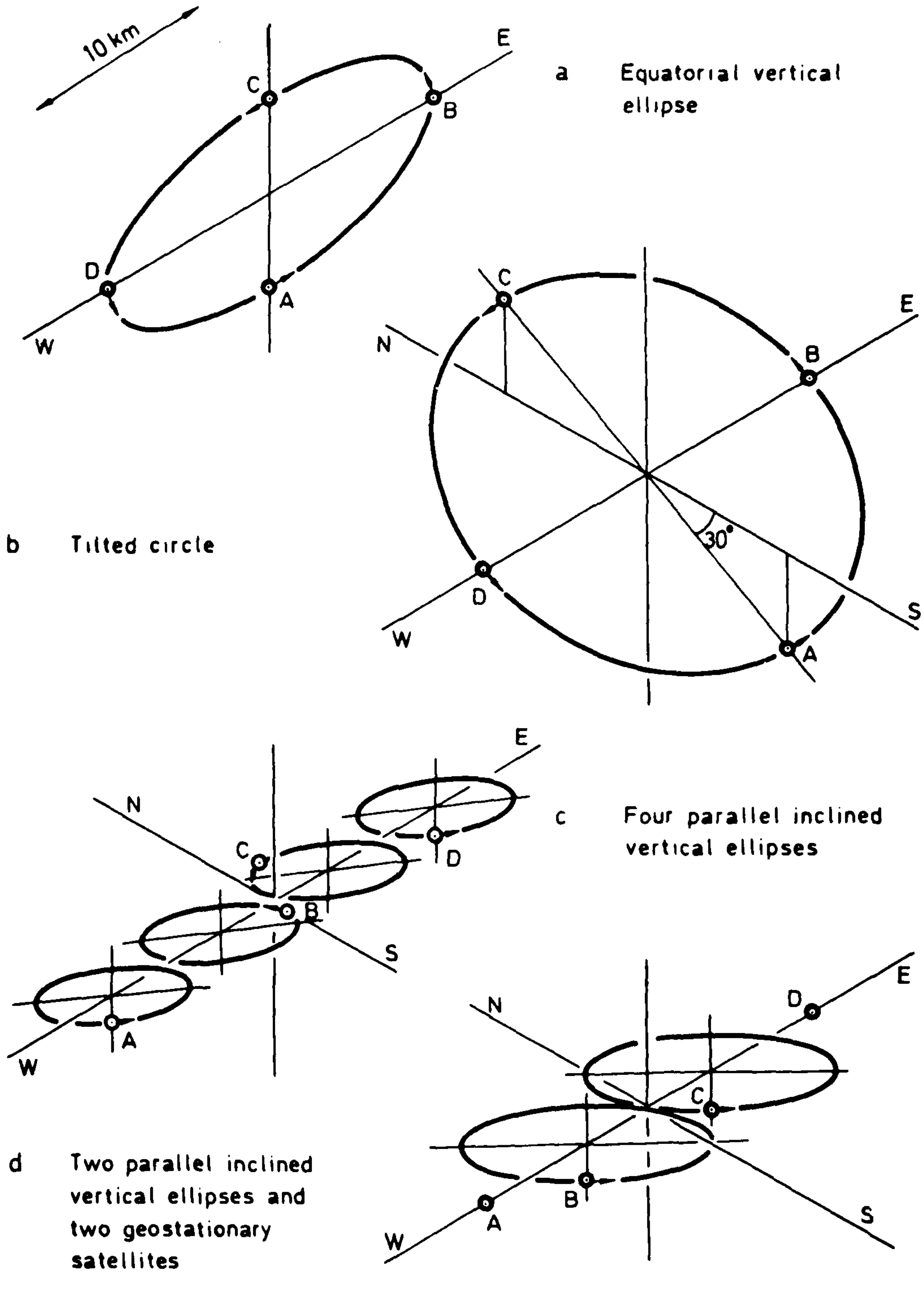


Fig 9a-d Comparison of four example configurations *(isometric projection)*

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17. Abstract

A preliminary examination has been made of some practical considerations affecting the choice of geometry for geosynchronous satellite clusters, including the constraints imposed by orbit dynamics, the effects of orbital perturbations and a possible need for spatial discrimination to allow re-use of inter-satellite link frequencies. Three cluster configurations which appear to deserve consideration involve satellites following, relative to the cluster centre,

(i) a common elliptical path in the equatorial plane,

(ii) a common circular path tilted at 30^{o} to the horizontal, and

(iii) separate elliptical paths in parallel vertical planes inclined to the equatorial plane.

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